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Development of the Second Generation Wide Field and Planetary Camera for Hubble Space Telescope[1]

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With the upcoming scheduled launch of *Space Shuttle Endeavor* early next month, the fate of NASA's Hubble Space Telescope will rest in the skilled hands of five experienced astronauts whose demanding tasks will include installing corrective optics made necessary by the telescope's precisely polished but tragically flawed 2.4-meter-diameter main mirror. In the case of the telescope's centrally located instrument named the Wide Field and Planetary Camera (WFPC, pronounced Wiffpick, for short), the corrective optics are incorporated in an entirely new version of the 280-kilogram (618-pound) instrument. Like its perfectly-functioning predecessor, WFPC-2 will serve to re-image the focal plane of the telescope onto large-format electronic detector arrays through a selection of 48 spectral filters ranging from far ultraviolet to near infrared wavelengths and will offer a choice of two magnifications. The second-generation instrument was already under construction as a backup when the telescope was launched carrying the first-generation instrument in 1990.

When NASA discovered that HST's main mirror was flawed, engineers, scientists, and managers at NASA's Jet Propulsion Laboratory turned their attention to configuring WFPC-2 so that its optical system would have a clear focus despite the mirror defect. The main components of WFPC-2 are illustrated in Fig. 1. This article traces the history of its development.

THE FIRST GENERATION WFPC

The instrument that became WFPC-1 was selected on a competitive basis through an Announcement of Opportunity issued by NASA in 1975. Prof. James A. Westphal of Caltech and his team (including JPL) were selected in 1977 to develop it as the prim imaging instrument, At the time of selection the camera was to be delivered in 1980 for a 1982 launch. The concept of the camera evolved rapidly in the early post-proposal phases of its design, ultimately acquiring the dual magnification that led to the name Wide Field (F/12.9) and Planetary (F/30) Camera.

Replacement instruments were to be available to support Servicing Missions at five year intervals. Delays and changes in the Shuttle development program caused delays in the development of both the ST and the scientific instruments associated with it. This resulted in delays to both the launch and the initiation of the development of "second generation" scientific instruments. In 1984 with the ST scheduled for launch in 1986, a decision was made to build a duplicate -- or "clone" -- of the first WFPC to ensure that the ST's imaging capability could be restored if problems arose in the original instrument. Dr. John T. Trauger of JPL became Principal Investigator. This second camera was to be delivered in 1988[3]. With *Space Shuttle Challenger*'s disastrous accident of January 1986, the planned launch of the HST was postponed to 1989. Clearly the second camera would not be required as early as 1988; hence its development was stretched out to preserve resources. In the interim, significant technical improvements were effected that would enhance its performance, particularly at ultraviolet wavelengths.

The ST--officially renamed the Hubble Space Telescope (HST) after the astronomer Edwin P. Hubble whose observations in the 1920s *showed* that the universe is expanding--was launched on April 24, 1990. At that time, the second WFPC was scheduled for delivery in the 1995 time frame.

SPHERICAL ABERRATION

The first images returned from the observatory in May of 1990 exhibited abnormal characteristics and various difficulties were encountered in "fine tuning" the telescope's performance. Westphal's science team and workers at JPL and the Space Telescope Institute reached the conclusion that the HST's images could not be brought to a sharp focus because of a flaw built into the telescope's optical system.

It was recognized almost immediately that if the main mirror of the HST happened to be the cause of the problem (as the result of having an incorrect shape), the fix would be relatively straightforward, at least for WFPC. This was because of the fortuitous circumstance that inside WFPC's optical system, miniature images of HST's main mirror are formed almost exactly on top of elements (a set of convex mirrors about a centimeter in diameter) that are used in relaying the telescopic images to the detectors. Therefore, a defect of the HST primary can be compensated by introducing an equal but opposite "defect" on these small elements. This is illustrated in Figure 2.

It was not initially known whether the defect could be ascribed to the main mirror alone, or was caused wholly or partly by errors in the smaller secondary mirror of the telescope. If significant errors of the secondary of HST were involved, a simple fix in WFPC could not correct the problem except within a limited field of view too small to be useful. The exact nature of the defect and the fact that it is restricted to the HST's main mirror were eventually well established by extensive studies in the year following the discovery of the problem.[4,5,6]

THE SECOND GENERATION WFPC

At the time HST was launched, and its optical flaw discovered, many parts of WFPC-2, including its optical components, had already been fabricated. However, the instrument was still about four years away from its planned date of completion. Under the pressure to recover from the defect of HST, the schedule to complete WFPC-2 was accelerated, and to its list of functional requirements was added the requirement that its optical system be modified to correct the spherical aberration of the telescope to the fullest possible extent.

This would require not only that the components be manufactured and aligned to very tight tolerances in the instrument, but that the instrument itself be aligned with excruciating precision within the telescope -- a precision more exacting than the telescope's instrument-mounting latches were designed to provide. If the requisite precision of alignment could not be maintained, the ability of HST to detect and resolve the faintest astronomical sources would not be restored

FIXING THE ABERRATION

To make the conceptual fix a reality, much work was needed. Some of the tasks to be undertaken were foreseeable at an early stage. The initial plan of attack included three key elements:

- to deduce accurately and with high confidence the actual error built into the HST optical system;
- to produce an appropriately revised optical prescription for WFPC-2 that will correct "the HST aberration;
- to accelerate the development of WFPC-2 by three years so as to meet a newly planned 1993 servicing mission launch date,

These tasks occupied the attention of many workers at JPL, the Space Telescope Institute, Goddard Space Flight Center, and those in industry for almost a year. Two approaches were possible. The first involved a painstaking series of investigations of the tooling and test procedures used in manufacturing and testing the HST's primary and secondary mirrors, The second approach involved diagnosing the optical system's performance using stat images recorded by the orbiting observatory. It was clear that high confidence in the conclusions of these diagnoses would be possible only if the two approaches led to essentially the same answers.

In fact, "reverse engineering" of a flawed optical system was an ill-posed mathematical problem whose solution required the invention of new methods. A variety of technical approached were investigated. A series of observations with the HST was undertaken to acquire a variety of stellar images for use in these analyses.

MEETING NEW AND TIGHTER ALIGNMENT TOLERANCES

During the winter of 1990 and the summer of 1991 great efforts were made to both predict and to measure the alignment stability of the camera within the telescope. The assembled evidence showed that slight movements might be taking place within the orbiting observatory, or within WFPC-1, which in WFPC-2 could (in the worst case) prevent the corrective optics from restoring the HST's performance to the necessary degree.

The ramifications were extensive. First, to allow for the known alignment uncertainty caused by the instrument's mounting within the telescope, it was decided early in the program to provide an active tip-tilt mechanism to adjust the pickoff mirror; so as to permit any anticipated latch error to be corrected by remote control from the ground.

Tighter alignment tolerances also posed a potential problem for WFPC-2: could the camera maintain its alignment internally to the required level of accuracy. Evidence suggested that WFPC-1's internal alignment in orbit was slightly different from the alignment that had been documented just before launch. This would not have been a problem in WFPC-1 (had the HST been perfect), but might indicate the possibility of a problem in WFPC-2 because of its new function of compensating for the HST's flawed mirror.

As a result of such considerations, JPL, and the science team decided in September 1991 to recommend that a second level of active optics be implemented in WFPC-2, in the form of actively tip-tilt controlled fold mirrors in all but one of the relay optics channels of the instrument.

To compensate for the added cost to develop and build the Active Fold Mirrors (AFMs), the decision was also made to eliminate four of the original eight channels of WFPC. in the resulting configuration, three of the channels would carry Wide Field Camera optics, while the fourth would carry Planetary Camera opt its. In this arrangement, the active pickoff mirror would guarantee alignment of the channel having a fixed fold mirier. The three AFMs would guarantee alignment of the remaining channels. These recommendations were accepted and the task undertaken with utmost priority.

in June 1991, before the above measures were discussed, JPL, in collaboration with Litton ITEK Optical Systems studied a conceptual approach that allowed active control of the WFPC-2 pupil alignment on-orbit. The approach would capitalize on ITEK's proven electrostrictive actuator technology. This study demonstrated that active pupil control would be technically feasible. To make it a realit y required, however, that ITEK and JPL work closely together to develop, flight qualify and deliver a set of flight articulated flight mirrors in nine months. This required a significant resource commit ment and a radically different approach to implementat ion, The development of the articulating fold mirrors was successful both technically and prog aromatically: The mirrors were available when needed to support the camera buildup, they were completed within cost, and they performed as advertised.

Another modification stemmed from the very tight alignment tolerances in WFPC-2. one of the possible causes of the on-orbit alignment variations suspected in WFPC-1, the highly complex pyramid mirror mechanism became a leading candidate. in WFPC-1, this mechanism provided two capabilities: focusing the instrument relative to the telescope, and "switching" between the lower and higher magnification relay channels. The "switching" capability was no longer needed in the 4-channel WFPC-2 configuration. Moreover, the focus capability could no longer be used in WFPC-2, because if the pyramid were to be moved axially, resultant misalignment of the corrective optics relat ive to the telescope would blur the images. On the other hand, if small adjustments in the focus of WFPC-2 relative to the other instruments proved to be necessary in orbit, the necessary capability exists in the HST and in COSTAR to adjust the focus, For t hese reasons, the decision 'was finally reached to replace the original pyramid mechanism by a fixed mounting so as to eliminate, insofar as possible, all risk of optical misalignment in the instrument.

SIMULATING THE TELESCOPE

To test WFPC-1, an optical simulator of the Space Telescope had been designed and built at Caltech and JPL in the 1980s to feed light into the instrument in the same way that the actual telescope would supply images to it. To provide for testing WFPC-2, the simulator (or "Stimulus", as it was called) had to be redesigned and rebuilt to reproduce as faithfully as possible the aberrated images delivered by the as-flown HST optical system,- a task that required almost two years to complete. The new Stimulus became t he ultimate gauge-block against which the flight instrument could be tested in a simulated space environment prior to launch. As such, it was subjected to extensive testing and validation, which established that the Stimulus performed to well within its very tight allowable tolerances.

To assure that WFPC-2 would meet its allowable RMS wavefront error tolerance of $\lambda/14$ (at 633 nanometers), the Stimulus itself was required to meet a wavefront error tolerance of $\lambda/20$ relative to the wavefront it is designed to produce. But the new Stimulus is designed to produce highly aberrated images, the result of a specific amount (about 0.4A RMS) of spherical aberration in the 11 S"1'.

This circumstance gave rise to difficulties of two kinds. First, the question of how to define the meaning of " focus" of a highly spherically aberrated system is complicated by the fact that the focal length of the system varies (by sever-al centimeters in this case) between paraxial and marginal zones. Consequently, in specifying and in validating focus, it is necessary to specify correct I y the zone of reference. Second, as much as 0.4X RM S of spherical aberrat ion was found to bc beyond the capability of industry-standard optical interferometers to measure reliably, although such instruments arc routinely capable of high precision when aberrations are near zero, as is usually the case. It is possible, of course, to construct a null lens to cancel the spherical aberration of the Stimulus, and this was done to facilitate alignment and wavefront validation of the Stimulus. From double-pass interferometry of the Stimulus with its 3-element null lens, an RMS wavefront accuracy approaching $\lambda/40$ was consistently demonstrated.

However, as experience in the manufacture of the 11S"1"s primary mirror made painfully clear, a null lens might itself introduce error-. To avoid this risk, the decision was made to base the fundamental validation of the Stimulus upon the classical Hartmann test, in which no null lens is needed, Suitable high-precision masks were fabricated by photolithography, to bc located at the entrance pupil of the Stimulus under test. The Stimulus was illuminated by a point source on axis. The resulting light patterns were recorded by a LORAL 800X S00 pixel CCD at an accurately known out-of-focus distance. These arc illustrated in Fig. 3. The positions of the centroids of the light-bundles at the CCD were compared differentially with the positions predicted by ray-tracing, based upon the intended optical prescription of the system. The method provides a focus uncertainty of about $\pm$ 0.005 inch ($\pm$ 0.13 millimeter), as compared with a conservative focus tolerance of twice as much for the Stimulus. The method also yields a measurement ofthil-d-order spherical aberrat ion with a formal precision corresponding to about $\lambda/100$ RMS, slightly better than the accuracy with which the actual spherical aberration of the 11S1' is believed to be known. The usc of Hartmann tests and interferometric tests employing the null lens (as well as other "sanity" checks also performed) were in accordance with an adopted policy of requiring at least two independent methods of verification of all critical parameters relating to WFPC-2..

Round-the-clock testing of the assembled WFPC-2 in a simulated space environment in JPL's 13-foot vacuum test chamber began in late April of this year and occupied about a month, as planned. During this time, the integration and test engineering team put the instrument through all of its paces, while the science team tested and calibrated the instrument. Test tar-gets fabricated by J i-beam lithography in JPL's Microdevices Laboratory and an array of ultraviolet and visible light sources in the Stimulus were used to evaluate WFPC-2's imaging capability and photometric response under the conditions that would prevail in orbit. Although a few minor glitches were encountered, and solved, in the ground support test equipment, WFPC-2 passed all of its exacting tests, leaving no doubt that once in the telescope, it will perform to perfection.

On June 2, with an exhaustive pre-ship readiness review of WFPC-2 successfully completed, the instrument and its retinue of ground support equipment began a three-day road journey in specially instrumented and air conditioned moving vans to Goddard Space Flight Center in Maryland, where further tests were made to confirm that the instrument would be compatible with COSTAR in a high-fidelity simulator of the instrument bay of HST. By mid-August, cm schedule, WFPC-2 was ready to be moved again, this time to Kennedy Space Center at Cape Canaveral for final installation and alignment of its delicate pickoff mirror prior to launch,

The flight of WFPC-2, along with COSTAR and other systems planned for installation in 11S'1', will be an exciting adventure, whose success will restore the long-awaited deep-space vision of the 11S1'. We should not expect, however, that the full capabilities of the newly serviced Hubble Space Telescope can or will be demonstrated in the first few days or weeks. Bringing the telescope and its array of scientific instruments safely and surely back to life after the planned five-day Servicing Mission is completed will be as painstaking and exacting a task as building them was.

ACKNOWLEDGEMENT

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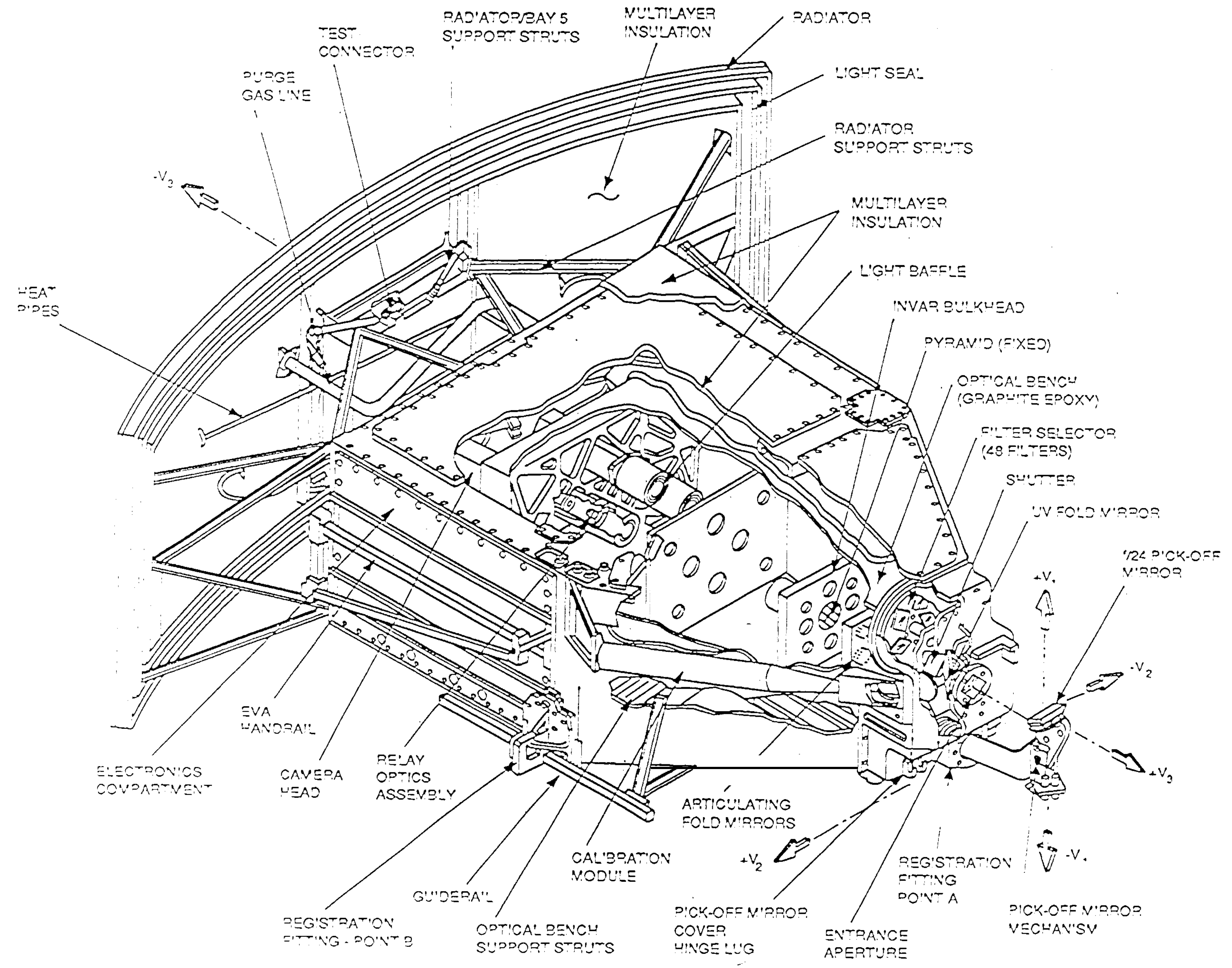

Fig 1 Vaughan & Rodgers

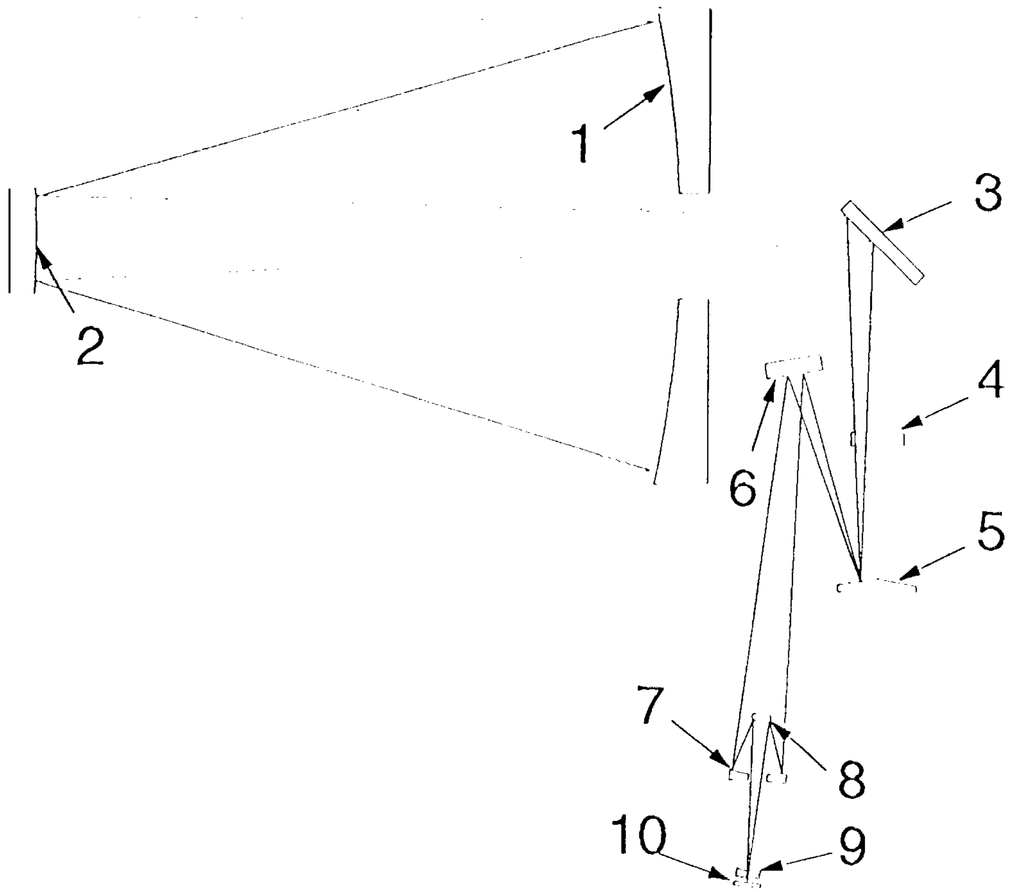

Fig. 2. Schematic optical layout of HST (elements 1 and 2); WFPC-2 pickoff mirror, filter, and pyramid mirror (3, 4, and 5); and one relay channel of WFPC-2 consisting of fold mirror, two-mirror relay, field flattener, and CCD detector (6, 7, 8, 9, and 10). The pyramid (5) is weakly concave. Elements 2-7 serve to form an image of the flawed HST primary (1) onto the relay secondary mirror (8), whose prescription in WFPC-2 contains a compensating correction.

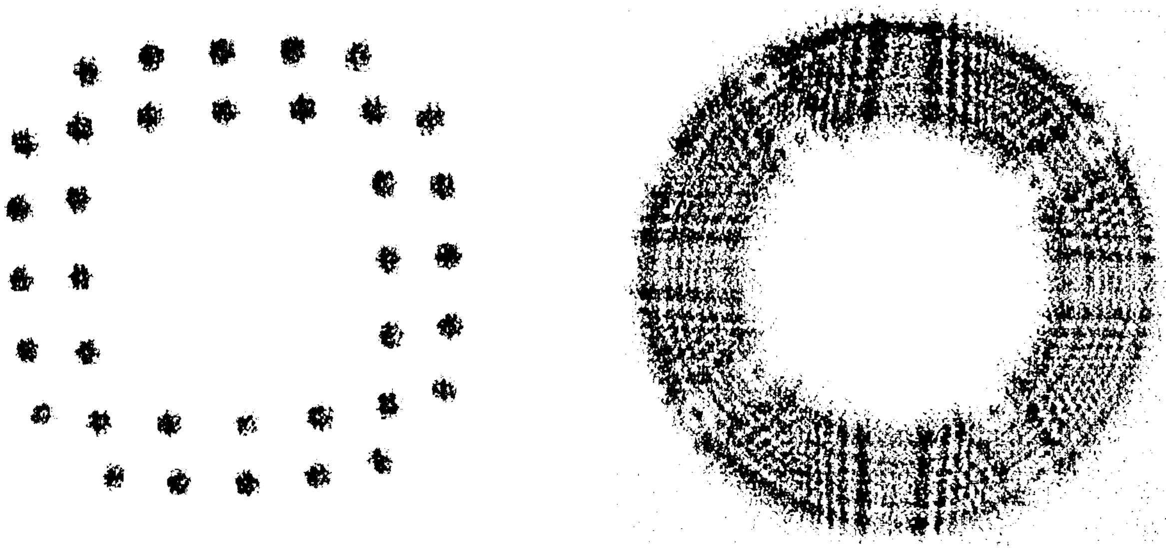

Fig. 3. Negative prints of out-of-focus diffraction patterns created by the Stimulus with a classical Hartmann mask of 36 holes in a rectangular array (left), and a complementary mask (right), consisting of eight opaque disks supported by thin vanes. Spherical aberration is manifest by the pincushion distortion of the Hartmann pattern on the left. Diffraction gives rise to bright "spots of Arago" at the centers of the shadows of the opaque disks, visible on the right.. The "Arago" mask was used to perform non-interfering focus tests of the Stimulus during environmental testing of WFPC-2. The illumination has a 5 nm bandwidth at 633 nm. The near-vertical, horizontal, and diaginal linear features are caused by secondary mirror support structures in the Stimulus and WFPC-2.